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# Attention[1]

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This is a review of the research on attention, time, and human information processing that has been carried out in my laboratory during the past 4 years. For the purposes of this conference, I will stress the concepts that are involved and their coordination to observables, and major conclusions from the experiments rather than detailed discussions of data. It would also seem to be appropriate for me to indicate generality when that is possible and to tell you what I know about the limits that must be imposed upon that generality.

The term "attention" has a number of very different meanings. Historically, there have been two major meanings; one implying selectivity in perception and the other emphasizing perceptual clarity. During the past 10 years or so, a number of new meanings have accrued to the term as a result of the recent surge of research in the area, and we seem to have reached a point where it is hardly useful to continue to use the single term. My work does not attempt to systematize this entire field. Instead, I am concerned with working out the details of one particular attention mechanism—one that may be described as a mechanism that controls the flow of sensory information by selecting among sensory inputs.

My approach is an indirect one in that I make inferences about this selective mechanism through measurements of certain of its temporal characteristics. A concept has evolved out of this, linking the present theory to a rather large body of theories that seem to have little or nothing to do with attention. I am referring to the concept of a time quantum or a unit of psychophysical time. At present, the time-quantum hypothesis is a central part of this theory and I will show how it is related to attention and to central information processing.

Two relevant reviews have appeared in recent literature. In 1963, White reviewed the many theoretical and experimental studies that bear upon the concept of a psychological unit of duration (ref. 1). More recently, a rather different review has been presented by Harter (ref. 2), a review of the various hypotheses of central intermittency in perception. Harter discussed seven different classes of experiments that have provided support for the idea of central intermittency and also the various theories of central intermittency that have been proposed. The present theory has some elements in common with most of the theories that Harter analyzes.

## EMPIRICAL PARAMETERS AND SOME EXPERIMENTAL RESULTS

This project began with a specific statement of a very old, largely philosophical proposition concerning attention. It is the idea that attention is limited in that one can pay attention to only a small range of sen-

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sory inputs at any one moment. The extreme form of this proposition is that one can attend to only a single input at any particular point in time and that attending to multiple inputs requires switching of attention from one to the other. Therefore, I thought that I could begin by setting up the working hypothesis that one can pay attention to only one thing at a time and that if one is paying attention to thing A at the time thing B occurs, it should require some length of time to switch attention from A to B. It seemed feasible to attempt to measure this switching time.

There are, however, immediate difficulties that arise when one sets out to do this, and very careful experimental procedures are required to surmount these difficulties. Some of these difficulties are inherent in the very simple notion that I have just described. For example, if one wishes to measure the switching time between A and B, it is necessary to be sure that a subject is, in fact, paying attention to A at the time B occurs. My experiments lead me to believe that one cannot safely assume that this is the case; under some conditions it may be the case, but usually a more detailed theoretical model is required to take into account the fact that ordinarily subjects cannot meet this criterion. Another requirement is that the switching itself must be accomplished reliably; that is, that attention go from A directly to B rather than via some intermediate channel. This calls for the use of experimental arrangements that are clearly defined for the subject and for adequate practice sessions.

Because the switching time is undoubtedly very short, a third requirement is set upon attempts to measure it. This is that the times of occurrence of the sensory inputs must be specifiable with a rather high degree of precision. These considerations and others led me to design experiments using very simple sensory signals. In all the experiments, the signals are spots of light and pure tones, both of which can be controlled precisely along the time dimension. I use lights and sounds to be as certain as is possible to be that the signals really are different things that cannot be attended to simultaneously. And, finally, the critical signal events are the offsets of lights and sounds rather than their onsets, in order that the locations of A and B will be well defined for the experimental subject so that he will be able to attend reliably and switch his attention reliably from A to B.

These considerations are not very systematic and I have not presented them at all fully, but they do give some indication of the reasons why I have done experiments the way I have. Also, they introduce the general logic of the experiments. Two very different methods of measuring the switching time of attention have come out of this. The first one has to do with measuring the length of time required for a message to travel through the entire system, from signal to response. These are experiments on reaction time. The basic idea is that if one could measure the time required to respond to a signal B when the subject is in fact paying attention to B at the moment it occurs, and then measure the time required to respond to B when the subject is attending to A at the time B occurs, then by comparing these reaction times one should be able to infer the switching time between A and B. This is one approach, and one that can be applied only indirectly, as I will explain in a moment. The other approach requires the experimental subject to discriminate the relative time of occurrence of two different things. If he cannot pay attention to A and B simultaneously, than his ability to judge whether A and B occur simultaneously should be limited by the speed with which he can switch attention between them. This second approach has led us to do a large number of experiments on successiveness discrimination—the ability of human subjects to discriminate the successive occurrence of different sensory events from the simultaneous occurrence of such events.

I want to go on now and describe some specific experiments. I would like to avoid details as much as possible, but because many of the details of procedure are of critical importance, as I will discuss in a

later section, I hope I do not create the impression of greater generality than is warranted.

### Successiveness Discrimination

One form of the successiveness discrimination function is shown in figure 1. It is a relationship between the probability of correctly discriminating the successiveness of a light and a sound and the time interval that elapses between the occurrence of the two signals. The time interval between signals is shown in figure 1 to extend in the positive direction from zero and it is so defined that these positive values mean that the visual signal occurs before the auditory signal. At zero, the objective time of occurrence of the two signals is simultaneous. And there is, of course, a negative side to this in which the auditory signal occurs first.

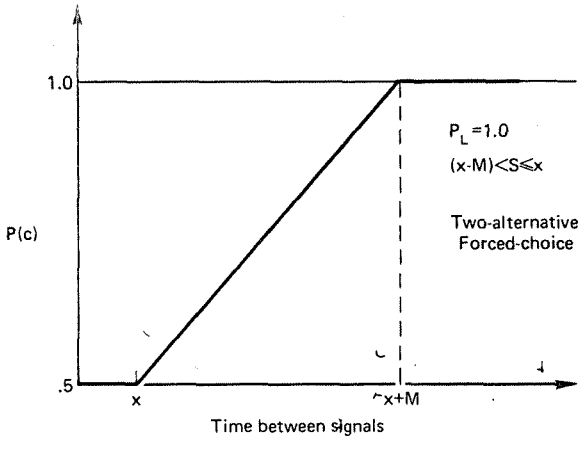


FIGURE 1.—Theoretical form of the successiveness-discrimination function.

The proportion of correct discriminations is plotted on the ordinate from 0.5 to 1.0 because a two-alternative, forced-choice method is used in which the subject is given two signal pairs on every trial and is required to decide which pair is the successive pair. This means that even when he is completely unable to discriminate between the pairs, the subject will still get one-half of the trials correct.

Figure 1 indicates that the theoretical function that is shown is the one to be expected only when the time interval between the signals in the simultaneous pair on each trial is within a certain range. One cannot assume that a light and a sound that occur simultaneously will be simultaneous psychologically because the effects of the two signals are conducted at different rates over the two sensory systems. However, it follows theoretically, as I will explain later, that, as far as this discrimination is concerned, the two signals in the simultaneous pair will be exactly equivalent to a psychologically simultaneous pair, provided that they occur within a certain range of times of each other. This range, translated into real time, is indicated in figure 1.

The theoretical successiveness function that is drawn in figure 1 is a linear function that has three parameters. One of these parameters is $P_L$, the probability with which the subject is paying attention to the visual channel at the moment the visual signal occurs. Figure 1 indicates that a function consisting of a single linear segment is to be expected only when $P_L$ is equal to 1.0. Furthermore, the other constraint—that it is sufficient for the interval of the simultaneous pair to fall within the range between $x$ and $(x-M)$—is satisfied only when $P_L$ is equal to unity. In our early experiments, we tried to arrange experimental conditions so that $P_L$ would meet this theoretical specification, and so that we could analyze the data by using this single linear segment.

The other two parameters are $x$ and $M$. The first of these is the time separation between signals at which the function just begins to exceed the chance level. In theory, $x$ is the interval between the signals at which the relevant neural effects produced by the signals occur simultaneously. Because afferent conduction time is slower in the visual channel, we expect $x$ to be positive—and we find that it is. The final quantity is the one of special interest. The function ascends from chance to 1.0, over the range between $x$ and $(x+M)$ milliseconds. If our interpretation of $x$ is correct, then the span of the function, the quantity $M$, is the mini-

mum time that must separate the two independent neural events for them to be discriminated as successive with complete certainty. Stated empirically, $M$ is the minimum time that must be added to the interval between the two signals to bring the probability of a correct response from chance to 1.0.

We have obtained successiveness discrimination functions that are quite well described by figure 1. We now know that figure 1 describes a limiting case that can be closely approached but not completely attained. The first experiment that I want to discuss does assume that the case described by figure 1 is actually achieved, but I will indicate later the extent to which that is not quite correct.

### Effect of Channel Uncertainty Upon Discrimination Reaction Time

The time required for a subject to make a response to a stimulus, when he is instructed to respond as rapidly as he can, is very different from one occasion to another. The amount of variance in such reaction times is especially great when the subject must discriminate between signals in order to determine whether or not to make the response on each trial. The reaction times to which I refer here are called discrimination reaction times. The subject is confronted with multiple signals, but he is required to make, or not to make, a single response. In a typical experiment, three signals are presented on each trial, two visual and one auditory. At the end of a certain fixed length of time, one of the three signals goes off. The subject has been instructed to release his hand from the key as rapidly as he can if either the tone or the right light goes off, but to withhold making the response if the left light goes off. At the beginning of each trial, a cuing signal is given. This signal tells the subject that if the stimulus is a positive one it will be in the visual channel, or that it will be in the auditory channel, or that it may be in either of the two channels. The subject knows that on every trial the negative signal, the left light, may occur and it does occur on one-fourth of the trials.

Two distributions of reaction times are obtained for the visual signal: one for those trials on which the subject is "certain" and one for the trials for which he is "uncertain"; the same is true for the auditory signal. Thus, four distributions of reaction times are obtained in this experiment.

We are interested in the effect of uncertainty because when the subject is uncertain there should be a larger proportion of trials on which he is paying attention to the wrong channel at the moment the signal to respond occurs. If uncertainty has only the effect of requiring the subject to switch attention on some trials, then, by looking at the increments of time that are added to reaction time as a result of uncertainty, we should be able to infer something about the switching time of attention. One way of accomplishing this is outlined in figure 2.

For a particular signal, either the visual or the auditory, we have the measurements that are shown at the top of figure 2. There is a mean reaction time and a variance for the case when the subject is certain and

Measurements

| Condition | Mean | Variance |
|---|---|---|
| Certain (t) | $\bar{t}$ | $\sigma_t^2$ |
| Uncertain (T) | $\bar{T}$ | $\sigma_T^2$ |

$$\bar{T} = \bar{t} + P\Delta \qquad (1)$$

$$\sigma_T^2 = \sigma_t^2 + P\sigma_\delta^2 + \left[\frac{1-P}{P}\right](\bar{T}-\bar{t})^2 \qquad (2)$$

$\sigma$ = Time increment added to t by uncertainty
P = Probability that uncertainty will add $\delta$ to t
$\delta$ = Distribution: mean = $\Delta$, variance = $\sigma_\delta^2$

From (1) and (2),

$$\sigma_\delta^2 = K\Delta - \Delta^2$$

With

$$K = \frac{\sigma_T^2 - \sigma_t^2}{\bar{T}-\bar{t}} + (\bar{T}-\bar{t})$$

FIGURE 2.—An outline of the derivation of the coefficient $K$, the effect upon discrimination reaction time of channel uncertainty.

when he is uncertain, and these are denoted by the symbols in figure 2.

Let $\delta$ be an increment of time that is added to reaction time as a result of uncertainty. We need not specify anything more about $\delta$, not even that some value of it is added by uncertainty on every trial. The parameter $P$ is the probability that uncertainty will add such an increment on a particular trial. There is a distribution of values of $\delta$, which remains unspecified, except to say that it has a mean that is called $\Delta$ and a variance for which the symbol is shown in figure 2.

If uncertainty adds some unspecified increment of time to reaction time on some proportion of trials, then the mean reaction time under uncertainty will be related to the mean reaction time under certainty in the manner shown by equation (1) in figure 2. Reaction times will, on the average, be lengthened in proportion to the mean value of the added increments and in proportion to the percentage of trials on which such increments are added. Similarly, the variance of reaction times under uncertainty will be related to the variance of reaction times under certainty in the manner shown by equation (2). This equation is just a general form of the familiar equation for the variance of a sum and assumes that the size of the added increment is independent of the value of reaction time on each trial. This assumption is exactly the assumption that the theory would make and equation (2) is compatible with the theory. Equations (1) and (2) can be combined to eliminate $P$ with the result shown at the bottom of figure 2. The equation shows that the variance of the added increments is a function of a coefficient $K$ and of the mean value of the $\delta$ distribution. The coefficient $K$ can be calculated from experimental data as shown at the bottom of figure 2. It is a function of the extent to which uncertainty changes both the variance and the mean reaction time. The theoretical meaning of $K$ is contained in the equation, which shows that $K$ expresses a relationship between the variance and the mean of the distribution of the increments added by uncertainty. The advantage of this is that $K$ can be calculated from data in the manner shown, and that the value of $K$ is independent of the proportion of trials on which uncertainty adds an increment to reaction time. Because of this it is not essential to control rigorously the direction of attention.

### The Form of Discrimination Reaction Time Distributions

I would now like to describe a kind of theoretical model, which did not follow from the theory of attention, but arose as a result of a more detailed examination of some of the reaction-time data. This model not only seems to give us an additional interesting parameter, but it also provides an extension of the theory that is crucial for interpreting some of the parameters discussed in the preceding sections.

This model was obtained by plotting frequency distributions of discrimination reaction times for the certainty conditions and, at the beginning, simply abstracting common characteristics from the obtained distributions. Briefly, it was noticed that nearly all of the distributions had a span of approximately 150 milliseconds and that a very large number, well over half of them, were very similar in form. This abstracted form is shown in figure 3. The typical distribution has two peaks, one peak located about one-third of the way up from the lower limit of the distribution and the second peak, which is always a minor peak, is located about two-thirds of the way up. Furthermore, many of the distributions are very well described by three linear segments, as shown in figure 3.

An idealized distribution, like the one shown in figure 3, strongly implies a quantal process. Figure 4 shows a logical diagram of a message-transmission system that would generate a distribution of total transit times of the kind portrayed in figure 3. The quantity $A$ represents the total fixed transmission time between stimulus and response; that is, the transmission time that is the same on different trials. The variance of reaction

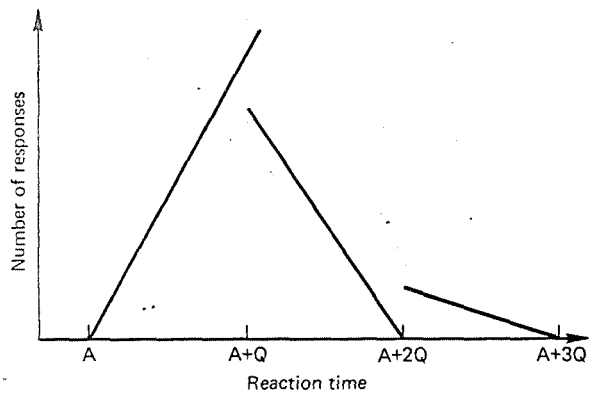


FIGURE 3.—A frequency distribution of reaction times generated by the model in figure 3.

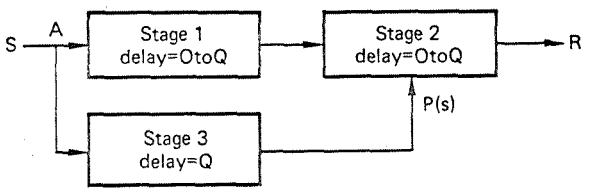


FIGURE 4.—A quantal model of information flow in discrimination reaction time.

time is contributed entirely by the three stages that are shown. A message enters stages 1 and 3 simultaneously and it is required to remain in stage 1 for some length of time that is equally likely to be any value from 0 to $Q$. It remains in stage 3 for exactly $Q$. After it leaves stage 1, it immediately enters stage 2, which has a delay characteristic the same as stage 1. If the message has left stage 2 before it leaves stage 3, then the stage 3 branch has no effect upon the response. However, if the message leaves stage 3 before it has left stage 2, then there is some probability $P(S)$ that stage 3 output will cause the message to be delayed one more $Q$.

I have no desire to defend this specific model and I present it mainly to indicate a direction in which I intend to do further work. This model is only an illustration of a class of possible models that have the important property of consisting of central delay stages having quantal characteristics. The one particular model shown here provides a satisfactory fit to a large number of obtained distributions, but there are many that are not well fitted by it.

### Experimental Results

One comprehensive set of experiments has been completed in which the preceding measurements were all made on each of a number of experimental subjects. These data are available (refs. 3 and 4) and I will not repeat them here. Let me just summarize the major findings.

Enough data are obtained so that it is possible to estimate each parameter separately for each experimental subject. There is no averaging of raw data.

The major finding is that $M$, $K$, and $Q$ are equal in absolute magnitude. The average value obtained for $M$ was 54 milliseconds and $K$ and $Q$ both yielded means of 53 milliseconds.

The parameter $K$, which is determined from the effect of uncertainty upon reaction time, is determined twice for each subject, once for the visual signal and again for the auditory signal. These two values of $K$ do not differ. The size of $K$ is independent of sensory channel, and the value that is obtained for one channel is significantly correlated with the value obtained for the other channel over individuals. This same pattern of results is also obtained for $Q$. The time constant governing central processing, which is inferred from visual reaction times, is the same as that for auditory reaction times, even though average reaction times differ by a substantial amount.

I have concluded that these three major parameters directly reflect the action of a single temporal process, and I refer to this process by the term "time quantum."

Several years ago, after many years of wrestling with the idea, it no longer seemed reasonable to expect that the temporal characteristics of the electroencephalogram would bear any simple relationship to behavior. As most of you know, this was a widely proposed notion a dozen years ago, but it did not seem to lead to any convincing experimental evidence. With the behavioral

data that I have just described in hand, however, it was difficult to resist taking the next step, so we proceeded to obtain electroencephalographic recordings from the same subjects. We did this for the obvious reason that the behavioral quantum appeared to be very nearly equal to one-half of the period of the alpha rhythm; that is, to the interval between zero crossings of alpha.

The frequency characteristics of the alpha rhythm are very well known, and, of course, it was no surprise to find that the interval between zero crossings agreed rather well with the measurements of the behavioral quantum. The purpose of the measurement was to determine whether there is a correlation between the magnitude of the behavioral quantum and the alpha zero-crossing interval. The data showed the existence of such a correlation.

There was, however, one discrepancy in these data which, although small, was consistent and could not be overlooked. I want to emphasize it here. Each of the three behavioral quantum estimates averaged about 53 msec. The average value of the alpha interval was consistently 48 msec. The difference is small but crucial. Furthermore, the distribution of values of the behavioral quantum was skewed in the upward direction, suggesting that there might be measurement error, at least for some subjects.

## Theoretical Interpretation

These results suggest that the quantum represents a limit that is imposed on neural information processing. I have already hinted at an interpretation of this, which I will go into in greater detail now.

The linear form of the successiveness-discrimination function, and the conclusion that two independent sensory events must be separated by one quantum in order to be discriminated as successive 100 percent of the time, can be accounted for in the following way. To discriminate an event B as occurring at a later time than an event A when the two events cannot be attended to simultaneously, it may be necessary for the subject to note first the occurrence of event A, and then switch attention to monitor event B. If event B is seen to occur following the switching of attention, then B can be judged as later than A and the two events can be discriminated as successive. However, if A is seen to occur and B is found to have already occurred when attention is switched to its channel, then the two events are effectively simultaneous.

If attention is restricted by the quantum in such a way that it can switch from one channel to another not more than once during a quantum, say at the end of a quantum, then the probability of discriminating A and B as successive will be equal to the probability that the end of a quantum falls in the time interval between the two signals. Because the time of occurrence of a signal bears no relationship to the time base of the quantum, the probability of a switching point falling between two signals will be simply the ratio of the time interval between the signals minus $x$ and the duration of a quantum.

This leads to the expectation that the successiveness discrimination function will be a linear, one-quantum function like the one shown in figure 1. It is a corollary of this that the time that must elapse after a signal is presented before the next switching point occurs will be a duration between zero and one quantum and that all durations within that interval will occur with equal probability.

What is implied by the finding that the coefficient $K$ is also numerically equal to one quantum? The most direct interpretation of this can be seen by looking at the theoretical equation at the bottom of figure 2. If the increment of time that may be added to reaction time by channel uncertainty is always exactly one quantum, then the variance of the increments will be zero and $K$ will be equal to the increment itself, and, obviously, the increment itself will be its own mean. Therefore, the conclusion that uncertainty adds exactly one quantum of time to reaction time on some proportion of the trials and exactly nothing on the remainder of the trials is a sufficient conclu-

sion. If the added increment is due to the need to switch attention on those trials, then it follows that the time that is added to reaction time as a result of having to switch attention is always one quantum. This conclusion seems to be in conflict with the conclusion reached above in the case of successiveness discrimination. Yet, it is not in conflict because the time that is added to reaction time may not be the time required to switch attention.

This is where the third parameter is important theoretically. If stage 1 in the model shown in figure 4 has the characteristics ascribed to it, then, on a reaction-time trial when attention is directed at the wrong channel, the time that would have been spent in stage 1 is, instead, absorbed by the switching of attention and the message then enters stage 1 exactly at the beginning of a quantum and must reside therein for one full quantum. From this it follows that the time that is added to the total transit time for the message by the need to switch attention is always exactly one quantum. The time that must elapse before the next opportunity to switch will be, with equal probability, any value between zero and one quantum.

This synthesis is based on the assumption that the time base that controls the switching of attention is the same as that which determines how long the message remains in stage 1. This is consistent with the idea that there is a unitary quantum generator, and yet I must point out that it becomes arbitrary to an extent when we consider that stages 1 and 2 of the model in figure 4 are assumed to be independent of each other. The same time base controls attention and stage 1, but it seems that an independent time base with the same period controls stage 2.

The theory that is developing out of this work is one that deals with the temporal microstructure of human information processing. The concept of attention plays a central part in it. In many ways, the theory is similar to the filter theory that was proposed by Broadbent (ref. 5). The similarities will be evident in the discussion of the structure of the theory, which will be presented below. There are also marked differences between the two theories. For example, the present theory has not yet found it necessary to postulate a short-term storage immediately prior to the attention mechanism. The reason for this is that the experiments that have been done so far have been designed so that they do not depend on the characteristics of such a memory unit. A short-term memory is irrelevant to our present purposes. The theories also differ in their degree of explicitness, the present theory being completely explicit within well-defined boundaries, to the point of permitting quantitative tests. The theories also differ in the kind of data to which each is thought to be relevant. Broadbent's theory, as is well known, was designed to account for the handling of complex verbal messages and other kinds of temporally extended behavior such as vigilance. The present theory, on the other hand, deals with elementary sensory signals and with events that occur over small fractions of a second.

A logical structure lurks behind the concepts that I have discussed above. This structure interrelates the concepts and I would like to discuss it next. It is shown diagrammatically in figure 5.

### The Structural Theory

It is convenient to begin by defining a central processor through which some messages are transmitted between the stimulus inputs and the response outputs of the organism. There is no need to speculate about the operations that are performed by the central processor. It is sufficient to say that some messages pass through it and that appreciable lengths of time are required for their transmission. We go one step farther and suggest that within the central processor a message is transmitted through a series of stages and that each of those stages consumes a certain amount of time. The configuration of stages is highly flexible. Different configurations are formed to meet different requirements. The con-

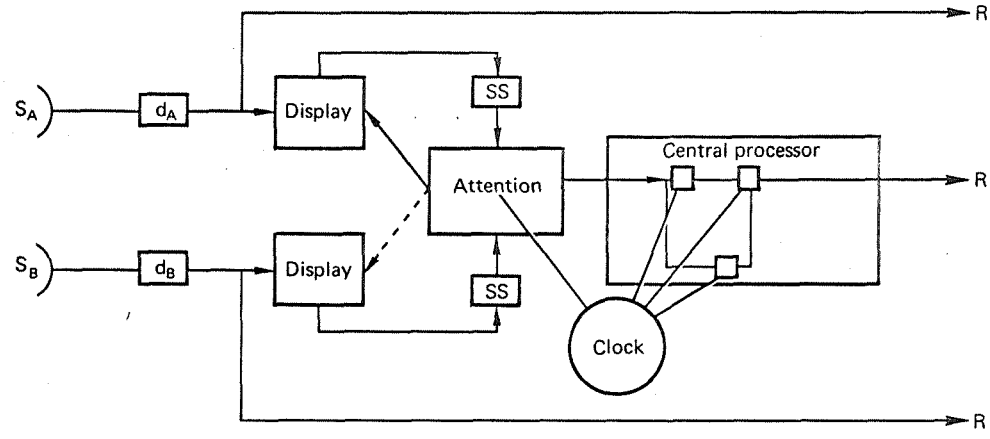


FIGURE 5.—Diagram showing some of the relations among the major concepts in the structural theory. $S_A$ = signal presented to channel A; $d_A$ = transmission time from receptor to display area; SS: switching signal.

figuration of stages is different for different information processing tasks, and, for a single task, different individuals may arrive at different configurations.

The admission of messages to the central processor is controlled by an attention mechanism. This mechanism is assumed to act as an all-or-none gate. Messages from only one sensory channel are admitted to the central processor at any one time. If attention is directed at a particular sensory channel at the moment a message arrives in that channel, then the message can be transmitted onward into the central processor without delay. But if attention is directed at channel B when a message arrives in channel A, the message is delayed by at least the time required for attention to switch from one channel to the other. One wonders what the factors are that determine which channel will be attended to at a particular time; there are undoubtedly many different factors that are influential in this respect, some of them to be found in the stimulus and others in various internal states of the organism. This theory does not attempt to classify or deal with these factors at the present time. However, it is important to point out that the theory places no restrictions on the way in which attention switches from channel to channel. No regular order of switching is assumed and no particular channel is assumed to have priority.

Not all of the messages that are transmitted by the organism pass through the central processor. Some messages may be transmitted via bypass routes. One reason for saying this is the finding that reaction times that depend only on the detection of the occurrence of the signal, rather than on a discrimination between the signals, seem to follow different principles. Detection reaction times are different in two important respects. In the first place, channel uncertainty has no effect upon detection reaction time when the subject is highly practiced, implying that attention is irrelevant. In the second place, the variance of detection reaction times is smaller than the variance that would be generated by any configuration of states within the central processor of the kind being defined here. It is one of the long-range goals of this research to define more precisely these two classes of messages—those which do and those which do not involve the central processor. The further development of the theory may make that possible. That there are bypass routes must be recognized. Their existence certainly complicates the experimental program.

It is necessary to assume that the attention mechanism receives identifying signals from each of the many sensory channels.

When a message arrives in a sensory channel to which attention is not directed, the channel is capable of signaling the attention mechanism to switch over to it. This implies a partial interpretation of incoming information at a level prior to the processor and prior to attention as well. The degree of detail that is required in the analysis of information at this level cannot be known until we have an adequate definition of the concept of sensory channel and something approaching a catalog of sensory channels. The effects of switching signals are undoubtedly highly probabilistic and, as a result, the switching of attention from channel to channel is usually an unreliable and noisy process.

Incoming sensory messages traverse sensory channels. These channels begin at the receptor organ and end in a hypothetical information-display area. Time elapses between the moment of arrival of the stimulus at the receptor and the moment of arrival of the resulting message in the display area. This time, which is referred to as an afferent conduction time, is an important quantity. Because we do not know where any display area is located, it is not possible to identify afferent conduction time with any particular electrophysiological latency. It is necessary that these temporal variables be included as parameters in the psychophysical theory.

It is not reasonable to assume that a particular stimulus, no matter how simple, produces a message in only one sensory channel. On the contrary, I suspect that every stimulus produces many messages in different channels, and that these different channels have somewhat different conduction times. Most tasks probably can be performed by utilizing information in any one of the many channels in which the stimulus produces an effect. This implies that afferent conduction time may not be a fixed quantity, even under fixed stimulus conditions. If a subject selects his sensory information from one channel at one time and from another of the possible channels at another time, then the afferent conduction time may change. We have seen several different instances in our experiments in which this seems to be happening. This is another very important reason why afferent conduction time must appear as a parameter and must be calculable for each particular kind of experiment.

A sensory channel, then, consists of a receptor, a transmission pathway, and a display area. Messages are admitted to the central processor by the attention mechanism from the display area of a sensory channel. The display area of a sensory channel is defined by its relationship to the central processor. A sensory channel consists of a set of all possible messages that can be admitted simultaneously to the central processor. In other words, a channel consists of all possible messages to which attention can be directed simultaneously. We must admit that we know very little about the organization of sensory channels that are defined in this way. We cannot state where the boundaries of the sensory channels are. Another long-range goal of this research is to provide the means for discovering the functional anatomy of the sensory systems that is implied by this definition. I have started by assuming that signals in different sense modalities, such as visual and auditory, generate messages in independent sensory channels. This does not, however, mean that I wish to identify sensory channel with modality; quite the contrary, I believe that there are also multiple sensory channels within each sense modality. We need a theory with quantitative power to enable us to map out these channels.

There is one more major concept to be discussed to complete this presentation of the theory, and that is the concept of a timing mechanism that controls the flow of messages in this system. The theory is specific about this and proposes that there is a timing mechanism, or a "clock," that controls both the attention mechanism and the central processor. The clock operates by generating a succession of time points. The evidence to date leaves it sufficient to state that under normal conditions these time points are generated at a fixed rate, a rate that is constant for a single individual but that differs to a small, although significant

and measurable, extent for different individuals.

The time points are generated at an average rate of approximately 20 points per second, which means that the interval between successive points is about 50 msec. This interval between successive clock pulses is referred to as the "psychophysical time quantum."

Two major functions are ascribed to the clock pulses at the present time. They control times when attention can switch from one sensory channel to another, and they control the flow of messages through the central processor by determining when the message can be transmitted from one stage within the processor to the next stage. These are two of the ways in which the clock coordinates and integrates the time flow of information.

What does this concept of a clock imply neurophysiologically? It suggests that there is some periodic process in the brain that is likely to be distributed widely throughout the brain and that controls the flow of information. It is known that there are extensive periodic brain processes. The most salient of these is the alpha rhythm of the electroencephalogram (EEG). In the human being, the alpha rhythm is a sinusoidal variation that has a very constant period. The voltage level crosses the zero axis approximately 20 times per second. It is possible that the alpha rhythm is one manifestation of the hypothetical clock. If this is the case, then we have an independent method for measuring the duration of the quantum, a method that is precise and very easy to apply. I do not want to imply that the electrical changes that comprise the alpha rhythm are involved in the information processing system in any causal way. For several reasons, that seems to be a questionable assumption and for the present time it is best to refer to the alpha rhythm as no more than a manifestation of the clock.

## SOME ADDITIONAL EXPERIMENTS

There are three additional experiments that I would like to describe briefly. The first two of these have modified and slightly complicated the ideas concerning the successiveness-discrimination function. The revised definition seems to be a more satisfactory one. These experiments also confirmed the correlation between the behavioral quantum and the alpha half cycle. These experiments have been described in a recent paper (ref. 6).

### One- and Two-Quantum Successiveness Functions

In the early experiments on successiveness discrimination, we did everything we could think of to make it possible for the subjects to perform at a maximum level and to encourage them to do so. This included giving them feedback on each trial, making their overall results known at the end of each session, and adjusting the difficulty of the discrimination so that it was a challenge to them.

Twenty-six subjects were run under such conditions. This usually involved from 30 to 40 experimental sessions for each subject. There is an initial practice effect, and a number of practice sessions must be conducted to bring performance to a stable level.

During practice, two of these subjects displayed an unusual phenomenon, which can be referred to as a quantal shift in performance. Very early in practice, both of them showed stable performance; that is, no systematic increase or decrease in total performance from session to session, over a period of 12 sessions. They were then changed to other experimental conditions that involved a similar task. Later, they were returned to the initial conditions and given additional training. In these later sessions, they reached a stable level of performance that was substantially above their initial level. Successiveness functions were fitted to their data for the early and the later sessions separately and it was found that in both cases the span of the function was reduced by a factor of 2 in the later sessions.

This change is shown schematically in figure 6(*a*). The single linear segment spanning two quanta represents the subjects' performance during the early sessions, while

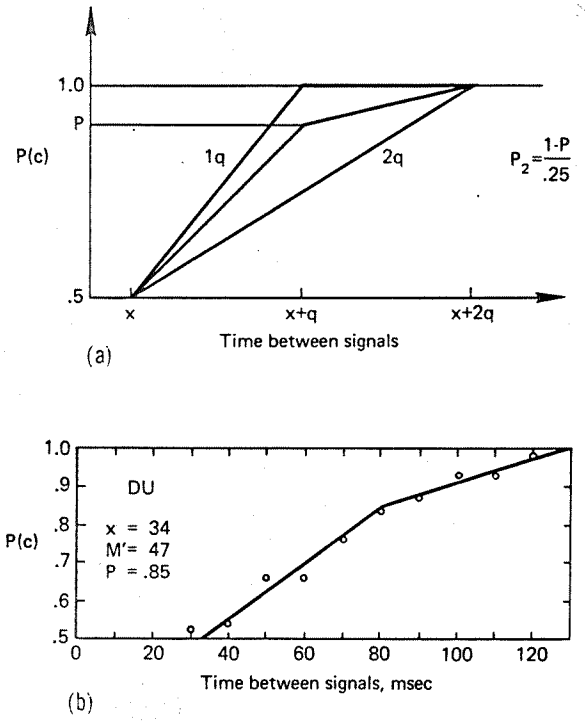


FIGURE 6.—(*a*) Theoretical one- and two-quantum successiveness-discrimination functions and their combination in the two-state model. $P_2$=probability of being in state 2; $q$=quantum size. (*b*) An illustrative set of data for a single subject with the parameters of and the lines representing the best-fitting two-state function.

the one quantum line represents their performance after they had received additional practice.

This observation suggested the possibility that a subject may be in either one of two distinct states over a long period of time. In state 1, the span of the function is one quantum, and in state 2 it is two quanta. Which state the subject enters might be influenced by practice, motivation, or other general psychological conditions.

I decided next to determine whether the proportion of subjects who enter state 2 could be increased by manipulating feedback to the subject and task difficulty. Five new subjects were chosen for this experiment and they were run with the usual procedure, except that for the first 12 sessions no feedback of any kind was given and the difficulty of the task was set at a relatively easy level.

Four of these subjects entered state 2 during these early sessions. The fifth subject went directly into state 1. Following the 12th session, feedback was introduced and the level of difficulty of the task was changed to the usual more difficult level. Additional practice sessions were conducted until the four subjects leveled off at a new, higher level.

The hypothesis that $M$ is two quanta in state 2 and one quantum in state 1 was supported in this experiment, both by the mean values of $M$ and by the high correlation between the two sets of $M$ values. The evidence for the existence of the two states seems fairly clear. We have not continued to pursue the interesting problem of identifying the variables that determine which state the subject enters.

### Two-State Successiveness Functions

Accepting the hypothesis of two states and the finding that the same individual may be in one state at one time and in the other state at another time, it is difficult to assume that all individuals can maintain either state over a length of time to the complete exclusion of the other state. Yet, that assumption is implicit in the earlier methods of interpreting successiveness data. A more realistic assumption would admit the possibility of a subject being in state 2 on some proportion of trials, even under experimental conditions that are designed to maximize performance. This might account for the earlier finding that the span of the successiveness function is slightly larger than the alpha half cycle.

This leads to a two-state model of successiveness discrimination in which the successiveness function is the weighted mean of two linear functions having the same value of $x$ but spanning one quantum in one case and two in the other. The weighting factor is $P_2$, the probability of being in state 2. An example of this two-state function is also shown in figure 6(*a*). It consists of two linear segments, each of which spans

one quantum on the time axis. The point of intersection of the two segments occurs at a value of $P(c)$ that is related to the probability of being in state 2 in the manner shown in the figure.

Data that are adequate for analysis by means of the two-state model have been obtained for 13 new subjects. Electroencephalograms were also recorded for these subjects in each experimental session. As in the earlier study, the average value of the alpha half cycle was found to be 48 msec. The average value of the behavioral quanta determined by means of the two-state model was also 48 msec. The correlation between the behavioral quantum and the alpha interval was confirmed.

To obtain data that are an adequate test of the two-state model requires setting the level of difficulty of the task so that it is relatively easy; that condition was used in this experiment. Under that condition, it is interesting to note that the probability of being in state 2 was not close to zero for any subject. This means that the one-quantum successiveness function is approximately correct, but only under very special experimental conditions. The generality of the one-quantum function is quite limited.

### Experimental Alteration of Quantum Magnitude

I should hasten to point out that we have not yet accomplished that which is implied by the title of this section. This is a project that is in progress. We have been working on it for the past 2 years and most of this effort has been borne by John Santa Barbara.

There are two main reasons why I want to find out where alpha fits into this story. In the first place, I am curious about the alpha rhythm itself. It is perhaps the most salient aspect of brain-wave recordings and we have never been able to identify its psychological or behavioral significance. In the second place, the temporal characteristics of the alpha rhythm can be determined easily, rapidly, and with a high degree of precision. With the proper equipment, one can accomplish this for a single individual in just a few minutes. This is in marked contrast with the behavioral methods that we use; such methods require experimental sessions spread out over many weeks to complete a single measurement. Therefore, if it can be established that the conclusion about alpha that I am suggesting is a valid one, we would have a very powerful tool to use both for further analytical work and for any attempts that might be made to apply this theory in practical situations.

We need further evidence of a different logical nature concerning the relationship between alpha and the quantum. Most of our evidence is at the present time only correlational and it is not adequate to support a strong conclusion.

Another approach is to try to exert experimental control over the magnitude of the quantum. If we could find a way to change the frequency of the alpha rhythm, we could then make measurements to see whether we get the same changes in the behavioral quantum. This project is an attempt to do that. Mr. Santa Barbara set out to try to find some agent or combination of agents that is effective in slowing down or speeding up the human alpha rhythm. This strategy was taken because of the greater ease of measuring the EEG, and it is more efficient first to find an agent that produces a reliable effect upon the EEG.

We hope to find an agent that will shift the frequency spectrum in the alpha range and leave the remainder of the spectrum unaffected. Many agents have been tried, most of them selected on the basis of reports in the literature. They include dextrose, fasting, oxygen inhalation, carbon dioxide inhalation, Diamox, alcohol, Librium, and Dexedrine. None of these agents produced consistent results. Most of them had very little effect at all, and when effects were noted they were in one direction for some subjects and in the opposite direction for others.

We would like to produce a change in peak frequency of at least 20 percent. In no case have we been able to produce a change that large. With some subjects, some agents appeared to produce a change as large as 10

percent, but even these changes, the largest ones we obtained, were very inconsistent from subject to subject. Speaking statistically, the results that we have obtained are consistent with the results recorded in the literature. Agents that are reputed to speed up the alpha rhythm do tend to do that, and those that are reputed to slow it down tend to do that. The effects, however, are inconsistent and very small in magnitude.

On the basis of the work we have done so far, we are led to conclude that the alpha rhythm is highly impervious to external modification and highly stable for a single individual over long periods of time.

We are continuing the search for an effective agent. We are currently investigating the influence of body temperature. There are many reports in the literature concerning this. These studies have reported consistent effects and have often shown in detail the functional relationship between alpha frequency and body temperature. We also get consistent effects with body-temperature changes. Once again, however, the changes do not exceed about 10 percent, at least over the temperature range that we have used.

I would like to mention an experimental result that seems to be emerging, but is still quite tentative. We have been trying to develop a method for changing body temperature that causes as little discomfort to the subject as possible. In the course of doing this, we are finding that if you change body temperature using a procedure that depletes water and salt, then you get the usual change in the alpha frequency. However, if you take steps to prevent the depletion of electrolytes and fluid, then, even though body temperature changes just as much, alpha frequency does not change.

## FUTURE RESEARCH

My research during the next 2 years will be directed mainly at two tasks: a more intensive experimental and theoretical analysis of reaction-time distributions and the influence of channel uncertainty; and a continuation of the attempt to alter quantum size and to apply this to a study of the relationships among the major parameters.

It required most of the past year to arrive at a more adequate definition of the one parameter *M*. The next step is to study reaction time in the hope of reducing measurement errors in those experiments. Also, there are other experiments underway that are designed to extend the theory to encompass other phenomena; these will continue.

This work promises to have generality because it seems to integrate very different kinds of data into what is still a simple and coherent theory. However, all the work has been done in only one laboratory and even the basic experimental results are not yet firmly established. It is my conviction that the generality of the theory is sharply limited at present. In 2 years, at the present rate of progress, I may feel that the basic results are established. We will then be in a position to test the generality of the theory along other dimensions.

Useful empirical generalizations will be difficult to acquire. For example, consider the question of successiveness discrimination. I commented above that the experiments on the two-state successiveness function demonstrate that the one-quantum function is useful only under very limited conditions. The two-state function introduces a new parameter that has been shown to influence this behavior extensively. I am afraid that I can only make crude guesses about the variables that influence this parameter. Furthermore, I know from a number of other experiments that successiveness functions at the present time have meaning only within a very restricted discrimination context. They have all been obtained using a forced-choice method. Other psychophysical methods, which seem more similar to situations that one might encounter in applied settings, give results that I cannot reconcile with the forced-choice results at the present time. In a yes-no context, there seem to be still other parameters operating, and we have not yet succeeded even in identifying them.

As another example, take the conclusion stated above that channel uncertainty adds a quantum to reaction time on some trials.

For one thing, I know that this conclusion applies to a situation that involves a single response. Whether it would apply if the subject also had to select among responses is something that we simply do not know. I am quite sure that we would find a much more complicated set of relationships with multiple responses. Also, I know that this conclusion does not apply to detection reaction times. Finally, I also know that if one complicates the stimulus configuration in the discrimination reaction time experiment by doing nothing more than adding a fourth signal, an additional negative signal in the auditory channel, the conclusion does not apply. Distributions of the parameter $K$ that are then obtained do have a peak in the vicinity of one quantum, but they have a second peak at the two-quantum level and the average value of $K$ is quite different than it is in the three-signal case.

We also do not know anything about the possible effects of stimulus parameters, such as intensity, on the measured extent of the quantum, nor do we know whether similar results are obtained for combinations of sensory channels other than the one that has been used in all of my experiments.

## A NOTE ON APPLICATION

Despite the paucity of precise generalizations that would be useful in solving applied problems, I believe that it might be helpful to use this theory, or parts of it, in formulating certain applied problems and in designing relevant experiments. I can conceive of this being done in several different areas, assuming that information-processing efficiency is an important issue, such as designing displays, selecting personnel, monitoring the state of an operator, or evaluating the effects of environmental conditions, including physiological conditions.

The theory contains at least three general classes of parameters. There are four parameters that converge upon the quantum concept. Other parameters have to do with message transmission times, mainly within sensory channels. And, yet, other parameters are probability values, such as the probability of being in a particular configuration or information-processing state, and the probability of attending to a particular sensory channel.

From my point of view, the quantum concept is the most important of these because it is the source of integration for the theory, and I am sure that I have communicated that attitude in this presentation. However, the priorities that I attach to the various parameters are not necessarily those that should be assigned by someone who wished to use the theory in other contexts.

The magnitude of the quantum, except insofar as it establishes limits upon performance, is probably of minor significance as far as raw performance is concerned. I say this because individuals differ so little in quantum size, minimizing the value of selecting individuals according to this criterion, and also because it seems unlikely that the size of the quantum can be altered to any important extent.

On the other hand, quantum size may become important in complex tasks that involve many serial stages of information processing. Performance variance in complex tasks may be determined strongly by quantum size. However, we know very little at present about the extent to which the quantum concept is relevant to complex tasks.

I can illustrate this point with some of my own data taken from the two-state successiveness experiment (ref. 6). If one forms two groups of subjects by taking the six with fastest alpha and the six with slowest alpha, one can then compare the two groups with respect to their overall performance on the successiveness task.

The correlation between alpha and the behavioral quantum is close enough so that the average values of alpha and $q$ are within ½ msec of each other for both the fast-alpha and the slow-alpha groups. In spite of this, the groups differ hardly at all in overall performance and, in fact, the slow-alpha group shows slightly better overall performance. An inspection of the other

parameters clarifies this result. The groups are identical with respect to $x$, but quite different in the probability of being in state 1. The group with the larger quantum size was much more likely to be in state 1—enough to more than compensate for quantum size ($P_1$=0.57 for large $q$ group and 0.25 for the other group).

The implication of this is, of course, that some of the parameters other than quantum size may be much more potent determiners of performance differences.

## DISCUSSION

LLOYD A. JEFFRESS: Have you tried getting your stimuli in accordance with the phase of the alpha rhythm?

ALFRED B. KRISTOFFERSON: No; I have not tried that yet. I am reluctant to try it because there would be variability in the conduction pathway that would be hard to take into account.

HAROLD G. MILLER: What about electric shock as a method of changing your timings?

KRISTOFFERSON: Well, I have not tried that, but it would only be a very momentary thing.

JEFFRESS: Another possibility would seem to be to use a different sensory modality, say, touch and hearing, and use vision to drive the alpha rhythm.

JOHN W. SENDERS: Yes; possibly you could drive the alpha with touch.

JEROME I. ELKIND: Could you clarify one thing for me? It seems to me that you are talking about a clock running at 50 milliseconds while at other times you are talking about a delay of 50 milliseconds. Are you always assuming you are in synchronism with the clock?

KRISTOFFERSON: No; never. I am always assuming that the stimulus is completely independent.

ELKIND: Yet you said that things are going to be held there in stage 1 for 50 milliseconds.

KRISTOFFERSON: Because stage 1 and attention are controlled by the same clock; so if the message is held out of stage 1 waiting for attention to switch, then when it is admitted to stage 1, it will be admitted at the beginning of the quantum.

JOSEPH MARKOWITZ: It is synchronous gating.

MILLER: You only tried two of all your five senses. Maybe you could try heat too, which would be the third.

WARD EDWARDS: The reaction-time questions you are dealing with are very similar to those dealt with by people interested in the tradeoff between speed and accuracy. You did not say much about accuracy. I assume it was very high.

KRISTOFFERSON: It was. The probability of a wrong response was below 5 percent, between 2 and 5 percent.

EDWARDS: Suppose you manipulate the situation by means of your payoff matrix in such a way that you get 20 or 30 percent errors. You will expect to get substantial decreases in reaction times. How would that fit into this quantum conception?

KRISTOFFERSON: Well, I do not know what the effect would be on $K$; that is not immediately obvious to me. Parameter $K$ is a relation between two experimental conditions, both of which would be affected in the manner you are describing. Whether there would be a net effect on $K$ itself, I cannot say. I do not think there would be. Now, the other one, $Q$, I do not know. I would be sure that would be badly damaged.

MARKOWITZ: Do you have any thoughts on how you can go back from an $NQ$ state to an $(N+1)Q$ state? You were able to show a switch one way toward $N$. Then, do you have any feel for how you might go about getting them back?

KRISTOFFERSON: They would not go from the one all the way back to the two but they would go in that direction. In other words, $P_2$ would increase, but never all the way to one, once they had been in the one-quantum state.

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